DERIVATION OF ATMOSPHERIC TURBIDITY AT MIZUHO STATION, ANTARCTICA FROM THE BROADBAND SOLAR RADIATION MEASUREMENTS

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Abstract: Spectral measurements of the direct solar radiation were made by a pyrheliometer at Mizuho Station, Antarctica in the POLEX-South radiation measuring program. From the broadband measurement using cutoff filters, aerosol optical depths were derived by the Langley method without using a predetermined extraterrestrial solar radiation. Average aerosol optical depths were obtained as 0.020, 0.015 and 0.010 for the wavelength region 0–532 nm, 532–632 nm and 632–693 nm respectively. The Ångström turbidity coefficient $\beta=0.007$, wavelength exponent $\alpha=1.4$ and optical depth at 500 nm $\tau_M(500)=0.017\pm0.005$ were estimated.

Comparing with the optical depth measured in Antarctica in the past, present result was in good accordance with the recent measurements made by SHAW using the sun-photometer. Several difficulties in making the results accurate and some disadvantages in broadband measurements are discussed.

1. Introduction

An increase of particulate matters suspended in the atmosphere causes a change of the radiation field in the atmosphere, which necessarily leads to a change of the heat budget of the earth-atmosphere system (YAMAMOTO and TANAKA, 1972). The Antarctic atmosphere has been proposed to be taken as a reference for the state of worldwide air pollution, and several studies have been carried out on Antarctic aerosols (SHAW, 1978a; PETERSON and SZWARC, 1977; ONO *et al.*, 1981).

Atmospheric turbidity work from the observation of solar radiation depletion in the Antarctic started with the pioneer work by LILJEQUIST (1956) and compiled by KUHN (1972) and SHAW (1979a). The Japanese Antarctic Research Expedition (JARE) made preliminary measurements with a pyrheliometer and cutoff filters (KAWAGUCHI, 1974; SUZUKI *et al.*, 1977), and with a multiwave-length sun-photometer (MATSUBARA *et al.*, 1981) at Syowa Station.

Broadband measurements of direct solar radiation were made at Mizuho Station (70°42′S, 44°20′E, 2230 m a.s.l.) under the radiation measuring program of POLEX (Polar Experiment)-South. Details of the program were given by KUSUNOKI (1981) and YAMANOUCHI *et al.* (1981). One of the objects of the direct solar radiation measurements was to derive the direct and diffuse components in the global radiation, and another was to derive an atmospheric turbidity. In obtaining values for the atmospheric turbidity, there are many difficulties in the broadband measurements with a pyrheliometer, and the method by narrow band with a sunphotometer has been proposed to be superior (SEKINE, 1980).

In the present paper aerosol optical depths for the broadband spectral intervals were obtained by the Langley methods and Ångström turbidity coefficients were estimated from the observational data of 1979. Several causes of possible error in the results are discussed.

2. Measurements

The direct solar radiation was measured by an Eko-MS52F pyrheliometer set at a height of 1.5 m above the snow surface (Fig. 1). The pyrheliometer had an aperture angle of 4 degrees, a cover glass of fused quartz was on the aperture, and

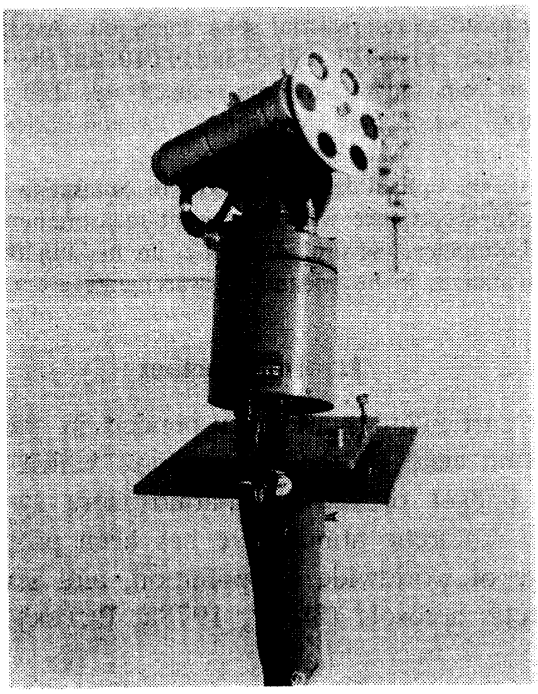

Fig. 1. Pyrheliometer with filter disk on the equatorial.

the detector was made of thermopile and had no equipment to compensate for the temperature dependence. Spectral measurements were made with cutoff filters: Schott OG530, RG630 and RG695 set on the rotating filter disk with two windows without filter and one for blind. The disk was rotated once a minute; each window had a duration of 10 s. The sensor and filter disk unit were mounted on an equatorial which was worked by a pulse motor controlled by a clock which was set in a data logger. The sensor was adjusted manually for the declination once a day using the image of a pin hole. The data acquisition system was as mentioned by MAE *et al.* (1981).

Rotation of the filter disk held out throughout the year; however, movement of the equatorial was troubled by freezing several times in the winter season, even though the gear box was supplied with grease oil for low temperature use. After all, all the oil was washed out to deal with the problem.

Field calibration of the pyrheliometer was done occasionally against the Eppley Ångström pyrheliometer standardized with the International Pyrheliometric Scale-1956. The temperature coefficient of the sensitivity was found to be $-0.0013/°C$. The temperature dependence of the filter cutoff point was not checked in the field. It was reported by ICHIKI (1976) to be as large as 0.12–0.18 nm/°C and to amount to more than 1% of the transpared solar radiation energy for some filter if the ambient temperature changes more than 50°C. However, the radiation intensity deduced from two filter measurements would not be so large since the errors cancel.

The cutoff wavelengths of the filter were 532, 632 and 693 nm and the average transmittances beyond the cutoff points were 0.913, 0.913 and 0.917 for OG530, RG630 and RG695, respectively. From these filter measurements, values for three wavelength intervals were deduced: region 1: 0–532 nm, region 2: 532–632 nm, and region 3: 632–693 nm.

3. Analyses

The transmittance of solar radiation through the atmosphere is mainly dependent on three factors: the scattering by molecules (Rayleigh scattering), selective absorption by gaseous constituents (in the present case, absorption by ozone) and scattering by aerosols. If we denote the optical depth with τ_R, τ_{O_3} and τ_M respectively, we may express the solar radiation $I(\lambda)$ at a given wavelength λ passing through the air mass m from the Bouguer-Lambert law as

$$I(\lambda)=I_0(\lambda)\exp\{-(\tau_R(\lambda)+\tau_{O_3}(\lambda)+\tau_M(\lambda))m\}, \qquad (1)$$

where $I_0(\lambda)$ is the extraterrestrial solar radiation.

From the combination of two measurements of radiation with cutoff filters, the measured broadband solar radiation $\bar{I}$ corresponding to the wavelength intervals λ_1 and λ_2 (which are the cutoff wavelengths) is evaluated as

$$\bar{I}=\int_{\lambda_1}^{\lambda_2} I(\lambda)\mathrm{d}\lambda. \qquad (2)$$

In practice, the sun-earth distance should be corrected at some stage. The average optical depth of Rayleigh scattering and ozone absorption $\bar{\tau}_R+\bar{\tau}_{O_3}$ for the wavelength interval λ_1 and λ_2 should be defined as

$$\exp\{-(\bar{\tau}_R+\bar{\tau}_{O_3})m\}\equiv\frac{\int_{\lambda_1}^{\lambda_2} I_0(\lambda)\exp\{-(\tau_R(\lambda)+\tau_{O_3}(\lambda))m\}\mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} I_0(\lambda)\mathrm{d}\lambda}. \qquad (3)$$

Then the average optical depth of aerosol scattering $\bar{\tau}_M$ is written as

$$\exp\{-\bar{\tau}_M\cdot m\} \equiv \frac{\int_{\lambda_1}^{\lambda_2} I_0(\lambda)\exp\{-(\tau_R(\lambda)+\tau_{O_3}(\lambda)+\tau_M(\lambda))m\}\,\mathrm{d}\lambda}{\int_{\lambda_1}^{\lambda_2} I_0(\lambda)\exp\{-(\tau_R(\lambda)+\tau_{O_3}(\lambda))m\}\,\mathrm{d}\lambda}$$

$$= \frac{\bar{I}}{\bar{I}_0\exp\{-(\bar{\tau}_R+\bar{\tau}_{O_3})m\}}, \tag{4}$$

$$\bar{\tau}_M = -\frac{1}{m}\ln\left(\frac{\bar{I}}{\bar{I}_0}\right)-(\bar{\tau}_R+\bar{\tau}_{O_3}), \tag{5}$$

where

$$\bar{I}_0=\int_{\lambda_1}^{\lambda_2} I_0(\lambda)\mathrm{d}\lambda\,.$$

The aerosol optical depth can be evaluated from eq.(5). Previously, we calculated $\bar{\tau}_M$ from eq.(5) using the known value of extraterrestrial solar radiation $\bar{I}_0$ (WORLD METEOROLOGICAL ORGANIZATION, 1971); however, there is a large discrepancy between several estimates of $\bar{I}_0$. For example, $\bar{I}_0$ for $\lambda \leq 532$ nm is estimated as 0.558 ly/min from the data $I_0(\lambda)$ by JOHNSON (WMO, 1971) and 0.524 ly/min from the data by THEKAEKARA and DRUMMOND (1971). Moreover, there were some uncertainties in the cutoff wavelength itself depending on the temperature as stated above. In the present paper the Langley method was used. Measured values $\bar{I}$ were plotted on an $m-\ln\bar{I}$ diagram as in Fig. 2. In the case of broadband analysis, unlike narrow band, particular care should be taken in using the Langley method. On account of the large variation of $\tau_R(\lambda)+\tau_{O_3}(\lambda)$ with λ within a wide wavelength interval, $\bar{\tau}_R+\bar{\tau}_{O_3}$ varies with m as seen from eq.(3). This is also the case for $\bar{\tau}_M$. However, in the present analysis $\tau_M(\lambda)$ is small and the variation of $\bar{\tau}_M$ was estimated to be $\pm 1\%$ within an airmass variation of ± 2. Using the estimated value of $\bar{\tau}_R+\bar{\tau}_{O_3}$ as a function of m, $\bar{\tau}_M$ was determined in the sense of least squares for a large number of measured values of $\bar{I}$ for every day. The average aerosol optical depth $\bar{\tau}_M$ was assumed to be constant throughout a day provided that the airmass was not so large. In the present work, analyses were restricted to the region $m \leq 4$.

The average optical depth for Rayleigh scattering and ozone absorption $\bar{\tau}_R+\bar{\tau}_{O_3}$ was previously estimated as a function of airmass m from eq.(3). $\tau_R(\lambda)$ by ELTERMANN (1964) was said to overestimate the optical depth (FRÖHLICH and SHAW, 1980) and rather small estimates of $\tau_R(\lambda)$ by FRÖHLICH and SHAW

$$\tau_R(\lambda)=\frac{P}{P_0}(8.3617\times10^{-3}+0.0047\times10^{-3}\times z)\lambda^{-(3.916+0.074\lambda+0.050/\lambda)}, \tag{6}$$

where z was the elevation in kilometers, was used. The standard pressure P_0 was set to 1013 mb, the average surface pressure at Mizuho Station was about 730 mb and the elevation was 2.23 km. As for $\tau_{O_3}(\lambda)$, absorption coefficients by VIGROUX (1953) were used for the average ozone amount 0.35 atm-cm. The airmass m was estimated (SHAW, 1978b) from apparent solar height h (°) as

$$m=\frac{1}{\sin h+0.15(h+3.885)^{-1.253}}. \tag{7}$$

The aerosol optical depth was approximately expressed by a power law func-

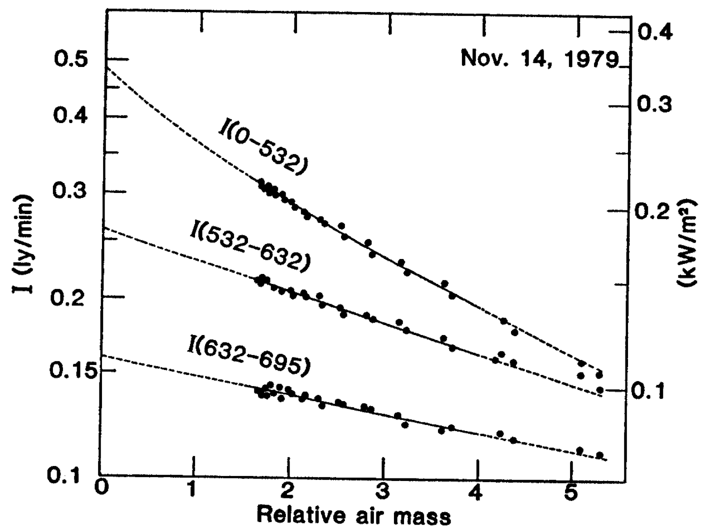

Fig. 2. Langley plots of solar radiation measured in three wavelength intervals.

tion of the wavelength λ as

$$\tau_M(\lambda)=\beta\lambda^{-\alpha}, \tag{8}$$

where β and α are the Ångström turbidity coefficient and wavelength exponent, respectively (ÅNGSTRÖM, 1961, 1964). Using α, the aerosol size distribution function of Junge type ($0<r<\infty$) can be expressed as

$$\frac{\mathrm{d}N(r)}{\mathrm{d}r}=-Cr^{-(\alpha+3)}, \tag{9}$$

where r is the particle radius, $N(r)$ is the number density and C is a constant, respectively, and β is propotional to the volume concentration of aerosols depending on the refractive index of the aerosols (YAMAMOTO *et al.*, 1968). In the case of broadband measurements, in place of the monochromatic wavelength λ in eq.(8), an effective wavelength $\bar{\lambda}$ was used. The effective wavelength $\bar{\lambda}$ over a wide wavelength interval was determind through eqs.(4) and (8) so as to satisfy the equation

$$\tau_M(\bar{\lambda})=\bar{\tau}_M. \tag{10}$$

Then the same type of equation as eq.(8) was applied to $\bar{\tau}_M$ as

$$\bar{\tau}_M=\beta\bar{\lambda}^{-\alpha}. \tag{11}$$

4. Results

In Fig. 2, one example of Langley plots of the measured solar radiation in three wavelength intervals is shown. As stated in Section 3, on account of the wide spectral width and the variation of the average optical depth, the solid line of least squares fit to the data points in region 1 shows some curvature. Standard deviations of the data points were less than or equal to 1% (in I), resulting in uncertainties of the optical depth of about 0.003 to 0.005.

During the observational period of 1979, only the data of about 20 days were analyzed, since the all-day long continuation of clear sky with negligible drifting snow was rare. The daily variation of $\bar{\tau}_M$ (region 1) is shown in Fig. 3. It is difficult to deduce any systematic variation in $\bar{\tau}_M$ from this figure on account of the large relative uncertainties and the short observational period.

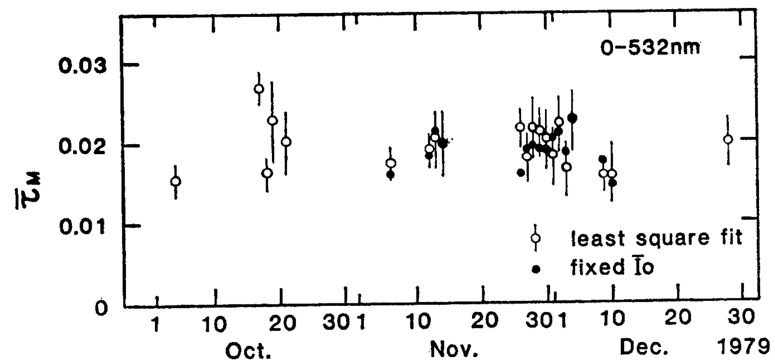

Fig. 3. Daily variation of aerosol optical depth for region 1.

Extrapolated zero airmass values $\bar{I}_0$ of the least square fitted Langley line, which corresponds to the extraterrestrial solar irradiance, are shown in Fig. 4. There are large variations in the figure, which cannot be due to the variation of the actual solar irradiance but rather must be due to the variation of wavelength interval—filter cutoff point—of the integral. A negative correlation is seen between $\bar{I}_0$ in regions 1 and 2, which may be ascribed to the variation of the cutoff point of the OG532 filter. $\bar{I}_0$ increases with the progress of the season in region 1; however, the contrary is true in region 2. It is obvious from this point that to assume a

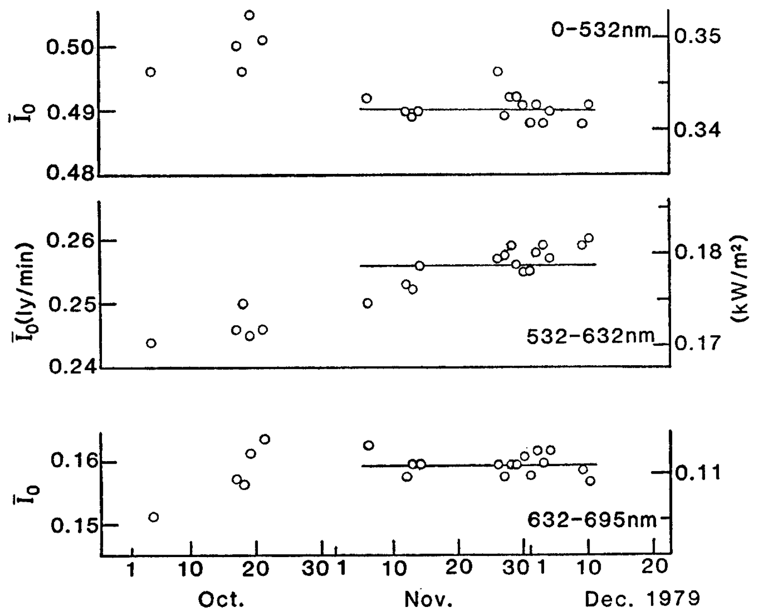

Fig. 4. Daily variations of extrapolated zero airmass values of solar radiation $\bar{I}_0$.

constant value of $\bar{I}_0$ in calculating the optical depth from eq.(5) is unrealistic. However, in a rather short period, for example, November 6 to December 10, $\bar{I}_0$ can be treated as a constant. Small daily variations seen in Fig. 4 in the region of constant may not be actual variations but simply an experimental error.

Another calculation of the optical depth from the constant value of $\bar{I}_0$ was tried. $\bar{I}_0$ was 0.490, 0.256 and 0.159 ly/min in regions 1, 2 and 3, respectively. These calculated values of $\bar{\tau}_M$ are also plotted in Fig. 3 compared to the original $\bar{\tau}_M$ obtained from the slope of the least square fitted line. The former might be much more reliable than the latter; however, no systematic differences are seen, and hereafter only the latter values are discussed.

Average values of $\bar{\tau}_M$ for a few days are listed in Table 1, with the standard deviation of daily value. $\bar{\tau}_M$ is also shown in Fig. 5 against the effective wavelengths $\bar{\lambda}$, which were 0.450, 0.591 and 0.662 μm in regions 1, 2 and 3 respectively. As seen in the figure, data points do not fall on a straight line.

The Ångström turbidity coefficient β and the wavelength exponent α were

Table 1. Average optical depths and turbidity coefficients.

Date	$\bar{\tau}_{M1}$	$\bar{\tau}_{M2}$	$\bar{\tau}_{M3}$	$\bar{\alpha}$	β	τ_M (500)
October 4–21 (5)	0.0202±0.0042	0.0169±0.0035	0.0141±0.0048	0.79	0.0107	0.0185
November 6–14 (4)	0.0192±0.0012	0.0142±0.0020	0.0102±0.0045	1.37	0.0064	0.0166
November 26–30 (5)	0.0205±0.0014	0.0147±0.0028	0.0073±0.0022	1.95	0.0043	0.0166
December 1–4 (4)	0.0199±0.0026	0.0157±0.0027	0.0084±0.0040	1.55	0.0058	0.0170
Total	0.0200±0.0027	0.0154±0.0030	0.0098±0.0047	1.40	0.0065	0.0172

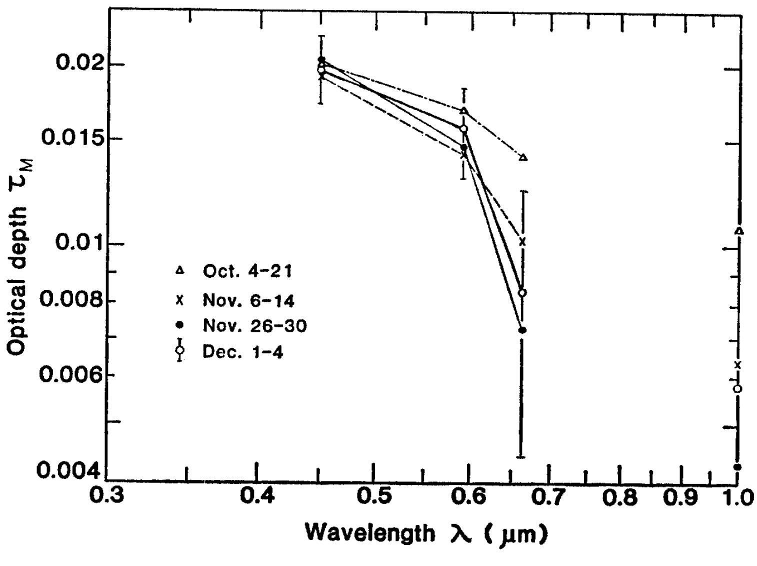

Fig. 5. Average aerosol optical depth as a function of effective wavelength.

evaluated from eq.(11) for the convenience of comparison to the other works, and for the reason that we have no strong evidence to insist on a different wavelength dependence because of large experimental uncertainties, though the data points do not lie on a straight line. Since $\bar{\tau}_M$ in region 1 is the most reliable of the three judging from the relative uncertainties, the mean of two values of α calculated from $\bar{\tau}_M$ in regions 1 and 2, and $\bar{\tau}_M$ in regions 1 and 3, respectively, was used for $\bar{\alpha}$. Using this $\bar{\alpha}$, β was derived from $\bar{\tau}_M$ in region 1. Values of $\bar{\alpha}$ and β for every few days are listed in columns 5 and 6 of Table 1. α originally calculated from each $\bar{\tau}_M$ of daily value varies widely from -1 to 3.5; however, the last result of $\bar{\alpha}$ lies in the range from 0.79 to 1.95 and β from 0.011 to 0.004.

5. Discussions

In the present work, there were two main difficulties in making the result accurate. One was that the turbidity was very small. The aerosol optical depth was more than one order smaller than the optical depth by Rayleigh scattering, which led to large uncertainties due to small relative uncertainties of Rayleigh and ozone optical depth. For instance, a difference of 0.02 in Rayleigh optical depth had been estimated between the data by ELTERMAN (1964) and FRÖHLICH and SHAW (1980) in the region 1 (0–532 nm). This difference is on the order of the present results. The estimate of ozone absorption is also uncertain; this has its strongest influence on the results in region 2. The wavelength dependence can be greatly varied by a difference in this estimate. Only the average amount of ozone (measured at Syowa Station) was considered in the present analyses. Thus it is very difficult to derive an accurate aerosol optical depth for clean air such as the Antarctic atmosphere using this method.

Another was in the broadband measurement compared to the narrow band (SEKINE, 1980). Method by a sun-photometer, which has been said to become stable in the calibration constant, would solve this problem. An average optical depth cannot be treated as a constant and depends greatly on the airmass, and an effective wavelength, needed to treat the spectral dependence, was also uncertain depending on the airmass. Uncertainties in the filter cutoff point and the transmissivity, partly on account of temperature dependence, might be the greatest cause of an experimental errors. Uncertainties in the extrapolated extraterrestrial solar irradiance $\bar{I}_0$ were brought on by this problem. Even if the Langley method was used, previously calculated $\bar{\tau}_R+\bar{\tau}_{O_3}$ would also depend on the change in the wavelength interval—cutoff wavelength—though it was small. Uncertainties in the spectral solar irradiance itself as stated in Section 3 were another problem. The temperature dependence of the transmissivity of the quartz window also had to be taken into consideration.

The effect of the solar aureole in overestimating the direct component was estimated to be 10% at most for 4 degrees of apparture angle from the work by ARAO (1978). Considering the accuracy, it was neglected in the present work.

On account of many uncertainties, the reliability of the present results was not high. In the present work, experimental accuracy was assumed to be ±30%. In order to make accurate measurements, the wavelength dependence of filter transmissivities and cutoff point have to be monitored occasionally at several temperatures during the observation, or else the temperature of the filter element must be controlled.

Comparisons to optical depths measured in the past are made. In order to make a rigorous comparison, results are converted to τ_M at 0.5 μm (last column of Table 1 for the present). As stated by ÅNGSTRÖM (1961), the wavelength exponent α may have large errors and may lead to erroneous values of β (optical thickness at 1 μm), so it is appropriate to compare the optical thickness itself (in the measured wavelength region) rather than to compare the value of β.

Turbidity coefficients or optical depths obtained from the preliminary measurements at Syowa Station by JARE are considerably higher than the present value even after considering the more than 2000 m difference in the station height. KAWAGUCHI (1974) obtained seasonal average values of β using the method by YAMAMOTO *et al.* (1968) from pyrheliometer measurements in 1972. Those values were 0.048 to 0.070 in the sense of τ_M (0.5 μm), derived from the data at airmass 2. There was a systematic dependence of β on the airmass or the solar elevation and β was larger when the solar elevation was high. From the data measured in 1974 by the pyrheliometer with cutoff filters, SUZUKI *et al.* (1977) calculated α and β, which resulted in τ_M (0.5 μm) of 0.09 to 0.15.

One of the causes to make the optical depth obtained by JARE in the past larger than the present was in the method to calculate an optical depth. The systematic dependence of β on the solar elevation shown by KAWAGUCHI (1974) suggests an inadequate value for the extraterrestrial solar radiation $\bar{I}_0$. It might also be the case for the results by SUZUKI *et al.* in which fixed values of $\bar{I}_0$ were used in each wavelength interval. In the present study, if the fixed $\bar{I}_0$ obtained by JOHNSON (WMO, 1971) with the cutoff points 532, 632 and 693 nm were used, the optical depth τ_M (0.5 μm) would range from 0.03 to 0.05, which is much larger than the present results.

Recently, from sun-photometer measurements, MATSUBARA *et al.* (1981) (a full report will appear in the near future) reported τ_M (0.5 μm) to average 0.018 on a clean day at Syowa Station in 1980, which was just in accordance with the present value.

Many works concerning the aerosol turbidity in 1950s and 1960s were compiled by KUHN (1972). The earliest work in the table was by LILJEQUIST (1956), who measured a turbidity coefficient β to be 0.025 on an average at Maudheim in 1952 with α= 1.3, namely 0.062 in τ_M (0.5 μm). In the table by KUHN, τ_M (0.5 μm) varies widely from 0.02 at Mirny in 1956 to 0.32 at the South Pole in 1963. High values at the South Pole within a few years after 1963 were said to be the effect of volcanic ash from Mount Agung, which erupted in 1963. However, 0.044 in 1961 or 0.037 to 0.049 in 1957 at the South Pole seemed to be quite large.

In the recent work, SHAW (1982) derived an optical depth from the sun-photometer measurements. On the average τ_M (0.5 μm) was 0.012$\pm$0.005 at the South Pole and 0.025$\pm$0.010 at McMurdo Station. In Fig. 6, the vertical distribution of Antarctic aerosol optical depths is shown after SHAW. Our value at Mizuho Station τ_M (0.5 μm) = 0.017$\pm$0.005 is also shown in the figure. It agrees quite well

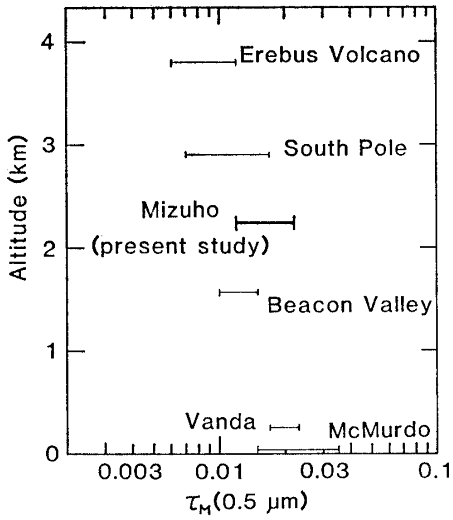

Fig. 6. Aerosol optical depth measured at several altitudes on the Antarctic ice sheet (after SHAW (1982) except for Mizuho Station).

with the vertical distribution given by SHAW. As for the vertical distribution, it has been suggested by KUHN (1972) that the Antarctic aerosol mass mixing ratio is nearly constant.

Only a few results were obtained for the wavelength dependence of the aerosol optical depths for the polar atmosphere to compare the present wavelength dependence. Measured result by SHAW was not published, though the inferred size distribution was reported in the literature (SHAW, 1979a). It was indicated that an aerosol number concentration size distribution was bimodal in the atmosphere column above the South Pole. It still remains for future research to derive an accurate wavelength dependence of the Antarctic aerosol turbidity.

The present result is also in good accordance with the optical depth at Mauna Loa Observatory (3380 m a.s.l.) in the least turbid case, comparing to the work by SHAW (1979b). The atmospheric turbidity in the Antarctic confirns that the air pollution level there is at the lowest level anywhere on the earth.

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